

Self-Induced Vibration of NGAS Space Pulse Tube Coolers

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ABSTRACT

Space cryocoolers are often used to cool the focal planes and optics of telescopes. Since telescope and focal plane jitter can affect the clarity of the image, space cryocoolers are designed for inherent low vibration. For very sensitive applications, many cryocooler systems incorporate active vibration control in addition to passive isolation from their mounting structures. The sole moving parts in all the NGAS pulse tube coolers, whether one, two or three stage, are the moving compressor pistons and their flexure supports that are inherently balanced in a back to back configuration. To further reduce the vibration below this already very low level, all the cooler systems are provided with single axis active control on the drive axis of the compressor that contains the moving piston masses. The cryocooler control electronics takes a signal from an accelerometer mounted parallel to the drive axis and feeds it back to the compressor motor drive signals to further reduce the vibration by >40dB. In this paper we present the self-induced vibration measurements made on a number of NGAS flight coolers including the single stage HEC cooler with both linear or coaxial cold heads and a micro cooler. We also present self-induced vibration measurements for the simultaneous operation of two HEC coolers mounted to the same platform.

INTRODUCTION

The exported vibration of a pulse tube cooler is caused by the acceleration of the moving masses in the cooler during its periodic motion. The acceleration comes from three main sources: 1) the reciprocating motion of the pistons, 2) the elastic response of the structures to the internally oscillating pressure and 3) the dynamic fluid-structure interaction in the cold head. Pulse tube coolers generate a lower vibration level than linear Stirling coolers because they do not have the additional vibration resulting from the cold moving displacer. For some applications, active vibration control may be desirable to further reduce the exported vibration from their already low levels.

Northrop Grumman (NG) back-to-back compressor modules inherently cancel most of a pulse tube cooler's exported vibration levels to low levels typically in the <200mN range. Since the motors are driven harmonically in anti-phase at their common resonant frequency that is fixed in the 30Hz to 120Hz range depending on the cooler, the output vibration signature in the

frequency domain consists of a series of spikes at the fundamental drive frequency and its harmonics. To assure that the moving mass balance is maintained over the typical 10 year lifetime and to further reduce the vibration along the moving mass axis, all NG coolers use an accelerometer mounted parallel to the piston motion axis as a feedback source for an error signal to the drive electronics. The drive electronics takes the error signal from an accelerometer mounted parallel to the drive axis on the compressor and corrects the drive waveforms to null the fundamental and 15 harmonics of the drive frequency. Therefore, even the lowest drive frequency cooler system is capable of active vibration control to a minimum frequency of 500 Hz, and the highest frequency coolers can be controlled to frequencies well above 1000 Hz. This paper presents the vibration test data collected on Northrop Grumman's HEC¹ and microcoolers.² Exported vibration data are presented for different input powers, cooler mounting techniques, and the simultaneous operation of two HEC coolers.

TEST APPARATUS

The exported vibration testing was conducted at Northrop Grumman's Cryocooler Dynamic Test Facility. Data were collected in two ways. The most common method is to mount the coolers on a fixture attached to a Kistler 9257B Dynamometer. In this facility the Kistler dynamometer can measure forces and torques in three directions with background noise force magnitudes below a few mN. The mechanical cooler and dynamometer fixture are mounted on a 2 inch thick steel plate which is bolted to a 70-ton seismic mass beneath and decoupled from the floor. The test apparatus design assures that a stable and rigid base is used in the calibrated force measurements. This gives a direct measure of the force and torque output. However, since the cooler is rigidly mounted to the massive fixture, the accelerometer output is too low to produce an error signal output at these very low vibration levels. Therefore the loop is closed around one of the Kistler force transducers parallel to the cooler drive axis. In this test mode, the well understood rigid boundary condition provides the data that an analyst can use to determine the effect on a more complex spacecraft structure. The dynamic data are analyzed and processed with a Data Physics' SignalCalc Dynamic Signal Analyzer. The SignalCalc Analyzer provides highly accurate measurements in the time, frequency, amplitude, and order domains with the capability of synchronous data averaging to recover data from the background noise. In the second test mode, the cooler is suspended while attached to its heat rejection fixture via low frequency "bungee" cords. In this case, the cooler has a very low frequency boundary condition and the loop can be closed around the flight accelerometer. Measurements are taken with reference accelerometers attached to the cooler and fixture and their output is converted to force from knowledge of the suspended mass. This is the other extreme boundary condition data that analysts can use. In both the rigid mounting and the suspended mounting, the cooler is operated with a purge gas rather than in vacuum in order to remove the additional fixture modes associated with the vacuum hardware.

HEC COOLER EXPORTED VIBRATION

We measured the very low self induced vibration of both the linear and coaxial cold head versions of our HEC cooler as shown in Figures 1A and 1B respectively. The linear cold head version HEC cooler is a flight cooler. The coaxial cold head version HEC cooler consisted of a flight compressor with a laboratory cold head similar to the flight design. The coolers were driven by a laboratory rack that contains a control card and flight software identical to that contained in the flight electronics shown in Figure 1C.

Figure 2A shows the HEC linear cooler hard mounted on the force table and the measured vibration output Figures 2B,C,D for each of the 3-axes. The vibration control loop was closed around the force transducer parallel to the compressor drive (Y) axis. The force transducers

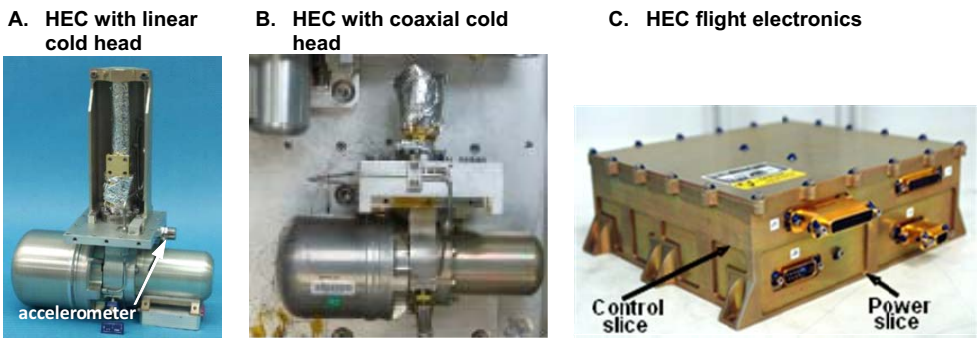


Figure 1. HEC coolers and flight electronics

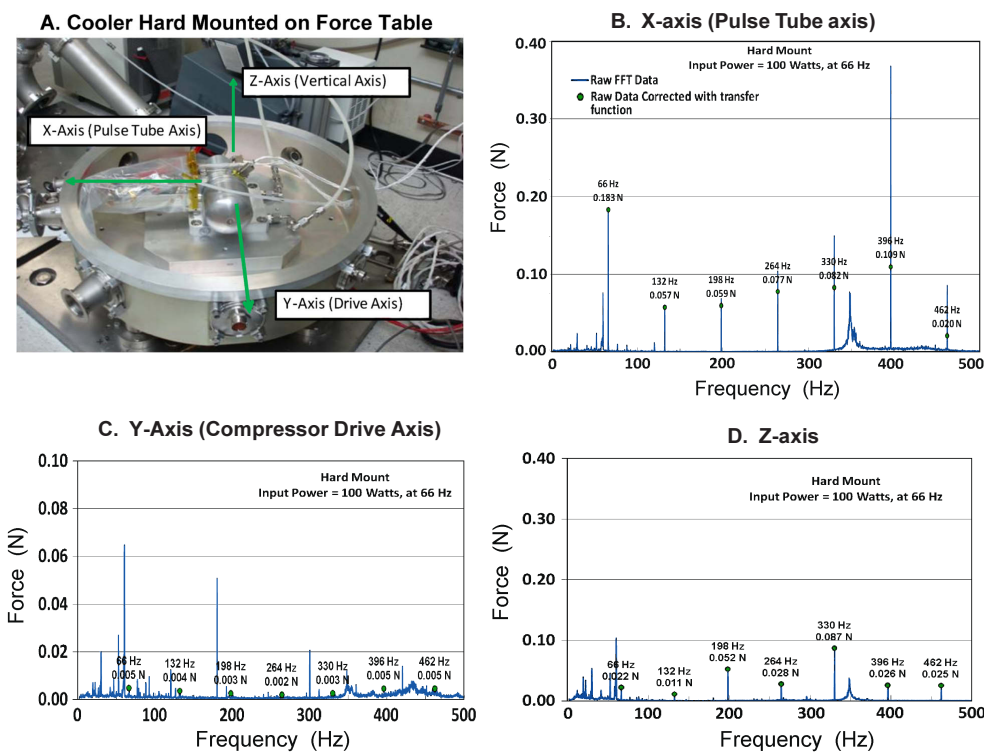


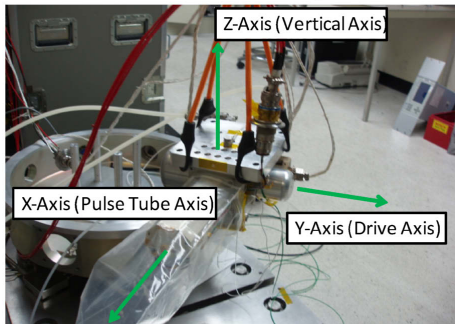
Figure 2. Vibration output of HEC linear cold head cooler hard mounted to dynamometer

parallel to the drive axis are used for feedback in the vibration cancellation algorithm because in this configuration the flight accelerometer has no output since nothing is moving. This provides the vibration output at the one extreme hard mounted boundary condition.

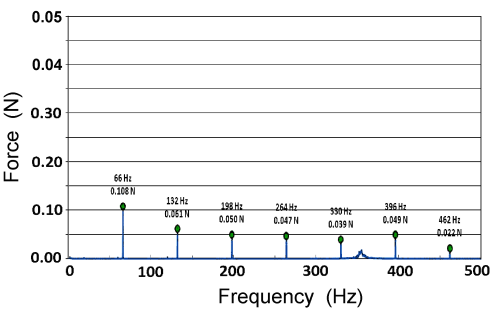
Both the raw data and more instructively the data corrected for the fixture response are shown on each graph. Along the actively controlled drive axis (Y) the vibration cancellation system reduces the forces into the few mN range. On the other axes all the harmonics are below 100 mN except for the fundamental along the pulse tube axis that is at 183 mN. These measurements were taken under steady state conditions in which the power is constant and both the cooling temperature and reject temperature are constant.

Since a real system has a mount with some unknown compliance we also measured the output at the second extreme boundary condition of the cooler suspended on bungee cords with

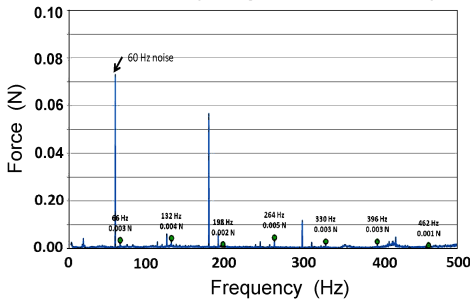
A. Soft Mounted Cooler suspended from Bungee cords. Includes rigid body water heat exchanger to remove heat while cooler is running



B. X-axis (Pulse Tube axis)



C. Y-Axis (Compressor Drive Axis)



D. Z-axis

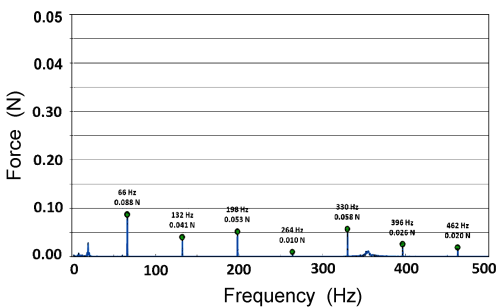


Figure 3. Cooler vibration when HEC cooler is soft mounted and control loop is closed on Y-axis accelerometer; Input power is 100W, drive frequency is 66 Hz.

the loop closed around the flight accelerometer that is shown in Figure 1A. Figure 3A shows the suspended cooler and Figures 3B, 3C, and 3D show the measurements when the cooler is hung by bungee cords.

A similar set of measurements was performed for a hard mounted coaxial cold head HEC cooler as shown in Figure 4.

We also tested the vibration output of two coolers on the same platform, each oriented at 90° to each other as shown in Figure 5. This orientation provides the opportunity to correct the pulse tube axis vibration of each cooler with the drive axis of the other cooler. Figure 5 shows that the synchronized coolers can each cancel the vibration of the other cooler along the other's pulse tube axis. There is a two order of magnitude vibration reduction at the fundamental compared to single unsynchronized operation.

MICROCOOLER EXPORTED VIBRATION

The microcooler is a very lightweight (900 gm) pulse tube cooler designed for space with the view that it could be used for tactical applications where 24/7 operation without degradation or change of performance for many years is required. The mechanical cooler has been packaged and its thermal performance has been characterized and documented.² Since the microcooler has a very low moving mass, a very low exported vibration is expected. Because of its potential use as a tactical cooler, we measured the exported vibration from the cooler when it was driven by both linear and tactical cooler drive electronics. Neither set of measurements included active vibration cancellation as used above. The flight drive electronics of Figure 1C could be used for

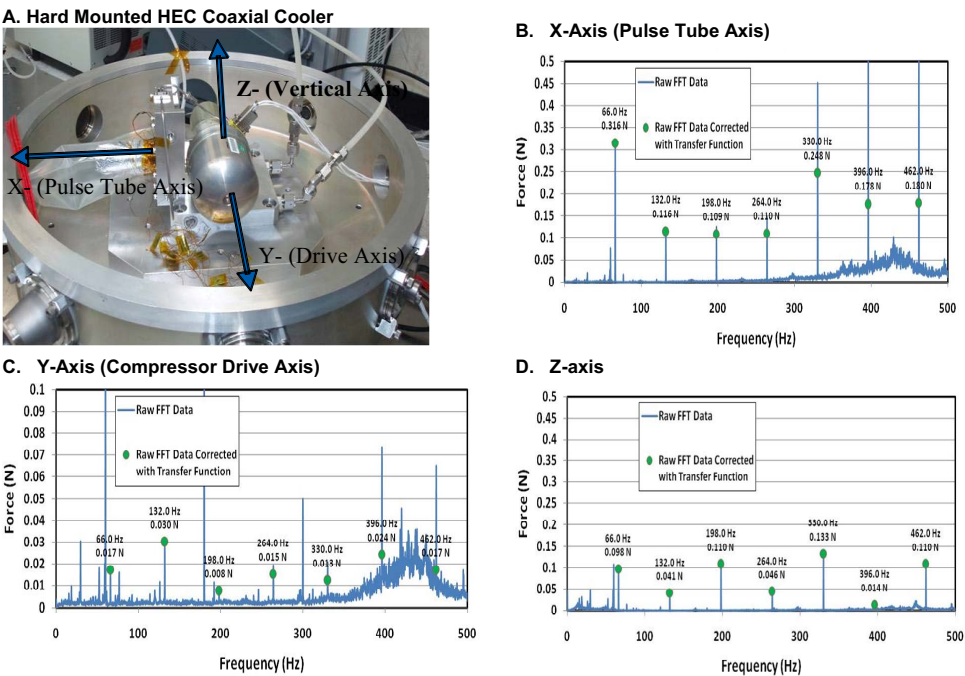


Figure 4. Hard mounted HEC coaxial cold head cooler vibration uncorrected and corrected for fixture response

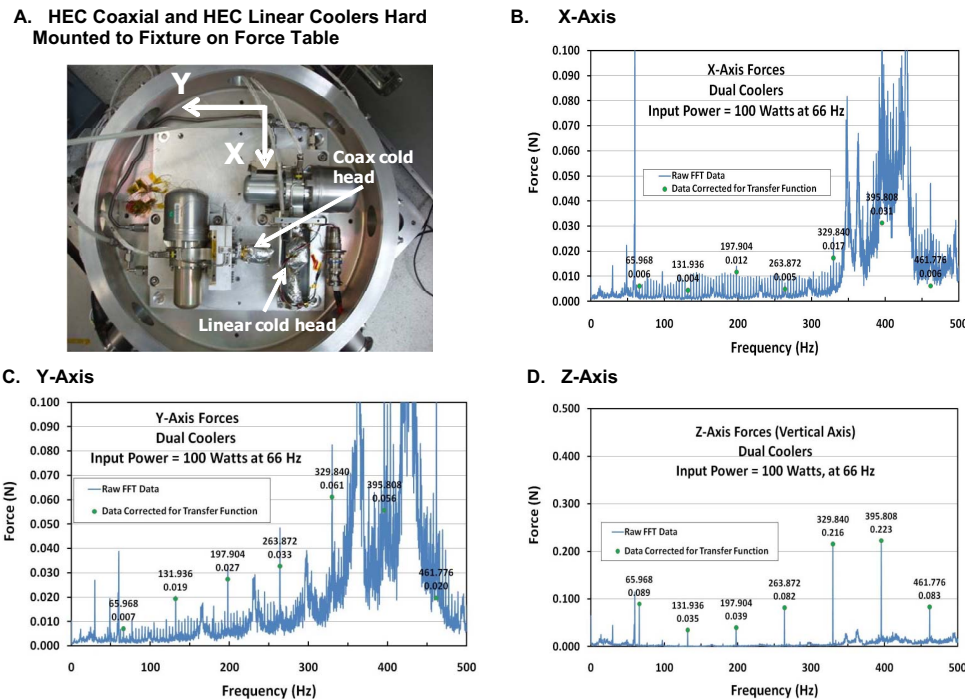


Figure 5. Two-axis vibration cancellation using two coolers oriented at 90°

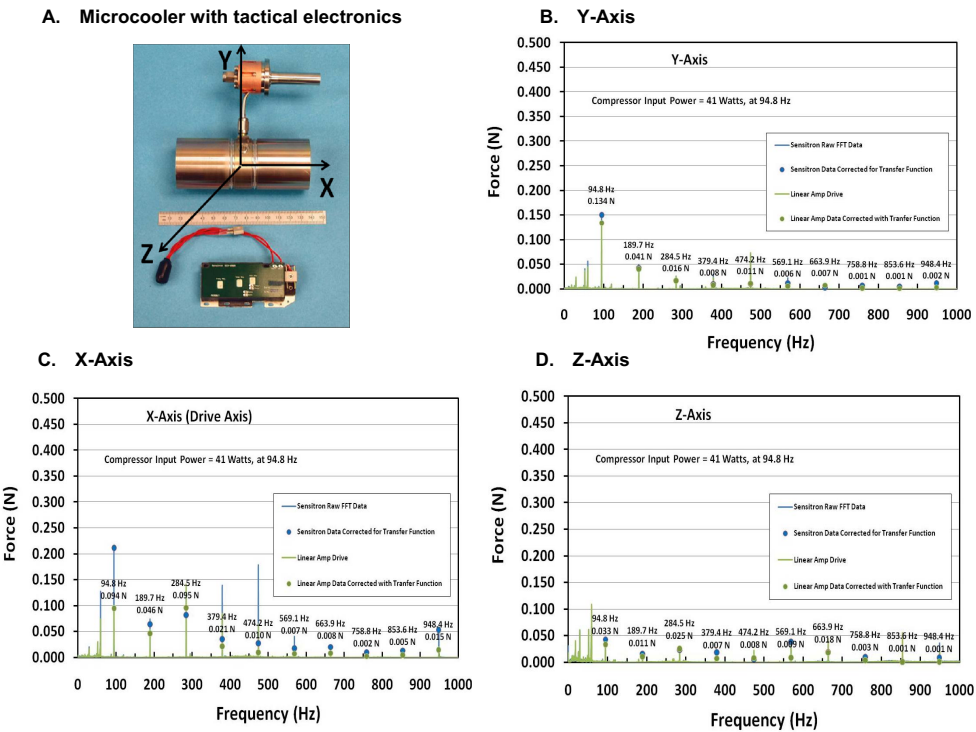


Figure 6. Vibration output of microcooler in 3 axes. No active vibration cancellation is used.

flight to reduce the vibration in the drive axis by a further 40dB into the few mN range if necessary. The cooler and its tactical electronics are shown in Figure 6A. The vibration output for the two different cooler drive techniques are plotted on each graph. The exported vibration from the tactical drive electronics is higher than the linear drive as expected. However, the actual values are lower than typical requirements for most space payloads even without active vibration cancellation. Note that even in the compressor drive direction the exported vibration is less than 0.1N without active control. Further information on the input power dependence of the exported vibration is given in a companion paper in this proceedings.²

CONCLUSION

The exported vibration for the HEC coolers with both linear and coaxial cold heads has been measured. When two synchronized coolers are mounted in a 90° orientation to each other, the exported vibration along each pulse tube axis is further reduced by an order of magnitude. The exported vibration of the microcooler shows a low exported vibration level in all axes without active vibration cancellation.

ACKNOWLEDGEMENTS

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